ONE-STEP METHOD FOR PRINTING STRAIN SENSORS ON GFRP: ASSESSMENT OF SENSOR PATTERN EFFECT

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ABSTRACT

This work has investigated the transfer of strain gauge patterns onto fibre-reinforced composites and their strain-sensing performance. Multiwalled carbon nanotubes (MWCNTs) and cellulose nanocrystals (CNCs) constitute the composition of the aqueous ink. The ink was transferred on the surface of a glass fibre-reinforced polymer (GFRP) composite in a one-step process using screen printing method. Two distinct geomatical configurations were printed: single line and conventional grid (consisting of 11 legs). The piezoresistive performance of the two strain sensors was investigated in tensile loading mode. The geometry of the strain sensors presented different characteristics for the piezoresistive behavior under tensile mode. At small strains, the single line configuration sensor was nonlinear and not sensitive enough to detect mechanical stimulus compared with grid configuration (GF=1.0). At the highest applied strain in the plastic region, however, single line configuration was much more sensitive (GF of 23.8 compared with 2.4 for the grid sensor). The methodology of the proposed strain gauge sensor attempts to eliminate the complex integration of external sensors, ensure compatibility with composite structures, and facilitate a novel manufacturing method. On the other hand, challenges to improve sensitivity (beyond 2) in elastic region and resolution are yet to be overcome. Thus, our current and future work focuses on improving the performance and quality of the transferred sensors.

1 INTRODUCTION

Structural health monitoring (SHM) plays a crucial role in monitoring the integrity and performance of structural composites. One of the critical components of an SHM system is the strain sensor, which enables the detection of mechanical changes. Typically, commercially used strain sensors are metallic gauge strain sensors bonded on the surface of the tested part. The surface of tested materials needs to be geometrically simple and adhere well to the sensor [1]. However, this bonding process increases complexity; the surface of the tested materials needs to be geometrically simple and must adhere well to the sensor.

Electrically conductive nanofillers offer piezoresistive properties that can detect mechanical changes when, for example, a nanocomposite is experiencing a strain. The difference in the conductive network can be quantified by measuring the sensor's change in conductivity (or electrical resistance) [2]. Important parameters that govern the piezoresistive performance are filler concentration and agglomeration [3]. One of the state-of-art piezoresistive strain sensors investigated in the literature is self-sensing nanocomposites. Self-sensing composites, however, provide limited control over their piezoresistive performance, and their mechanical properties may even be jeopardized due to the agglomeration of nanoparticles [4].

Transferring strain gauge sensors on the surface of composites has attracted attention recently due to its ability to avoid bonding and alter the composite's inartistic properties [1,5]. Groo et al. transferred a laser-printed strain grid sensor on the Kapton substrate on the surface of glass fibre prepreg using a rolling press [1]. They reported a sensitivity of 1.0. Luo et al. used direct laser writing to engrave strain sensors on a polyimide film bonded on a GFRP composite's surface [6]. They demonstrated that the sensitivity of the sensor could be controlled by altering fabrication parameters. As an alternative transfer method, inject printing was employed and has also been reported in literature, albeit used to print sensors on the surface of metal parts [7].

Here, carbon nanotubes (CNTs) and cellulose nanocrystals (CNCs) based aqueous-based ink were prepared to print different strain gauge patterns on the surface of glass fiber reinforced polymer (GFRP) composite using a screen printing method. The methodology of the proposed strain gauge sensor attempts to eliminate the complex integration of external sensors, ensure compatibility with composite structures, and facilitate a one-step manufacturing method. We demonstrated that the method reduces complexity by avoiding bonding between the strain gauge and the surface of the composite. Furthermore, the results showed that the geometry of the strain sensors influenced the piezoresistive behavior under tensile mode.

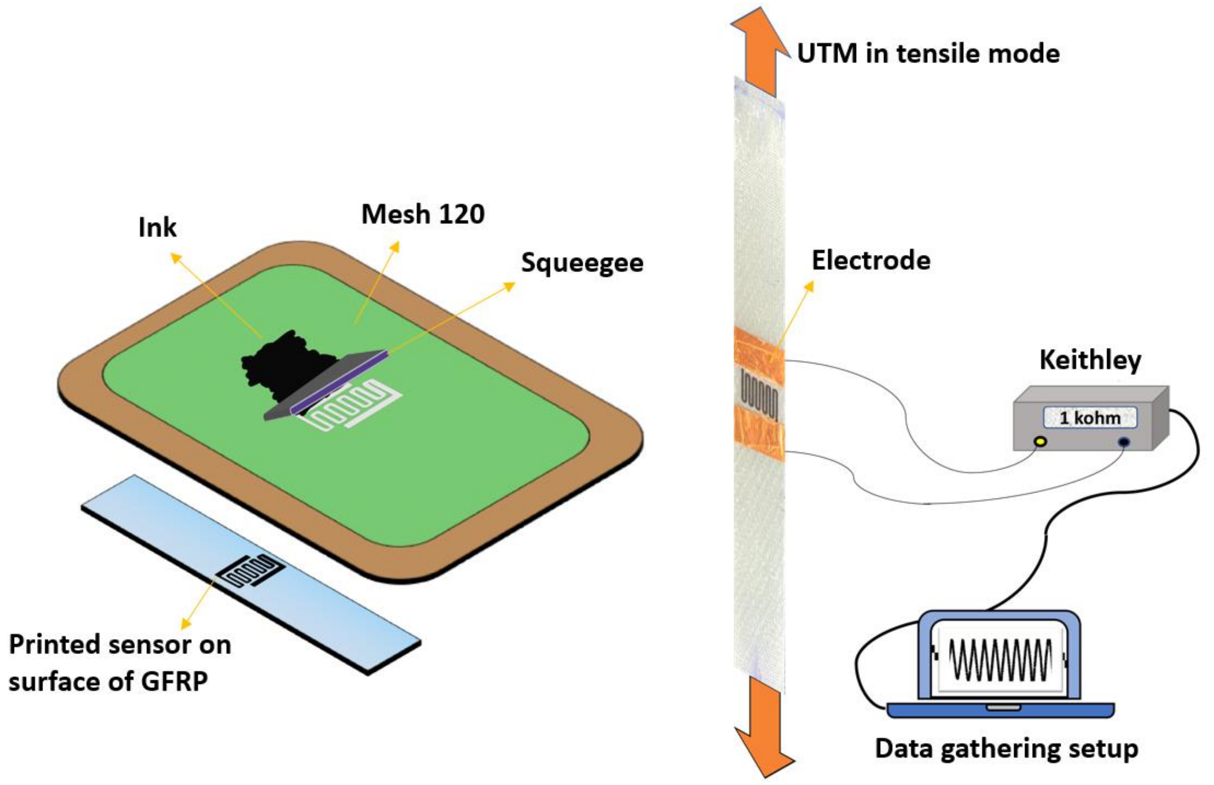
2 MATERIALS AND METHOD

All materials used in this study were used without purification. Multiwalled carbon nanotubes (CNTs) and cellulose nanocrystals (CNCs) were purchased from Sigma-Aldrich (United States of America) and CelluForce (Canada), respectively. Epoxy resin LR160 and hardener LH160 (weight ratio of resin/hardener is 4:1) were purchased from DostKimya, Hexion (Turkey). E-glass fabric (plane woven, 200 g/m^2) was purchased from Hexcel (USA). Screen mesh T90 was used.

3 FABRICATION OF STRAIN SENSORS

GFRP laminate composites were fabricated using a resin vacuum infusion process. Aqueous inks were prepared by first dispersing CNCs in water and adding an appropriate amount of CNTs to the mixture. The CNT/CNC (1:1 weight ratio) ink was then transferred to the surface of GFRP coupons using screen printing. Copper electrodes were attached using silver paint.

Schematic 1 summarizes the sensor preparation and electromechanical testing protocols. After the sensor was printed on the surface of the GFRP composite, it was subjected to tensile force in the UTM machine while the sensor was under a constant voltage difference supplied by the sourcemeter, Keithley 2400.



Schematic 1: Transfer of strain sensor onto GFRPs by screen printing and electromechanical testing

4 CHARACTERIZATION METHODS

Two-probe configuration method was used to measure the electrical resistance measurement of the sensors using Keithley 2400. Electromechanical testing was performed by Universal Testing Machine (UTM) (AGS-X, Shimadzu) in tensile mode, and simultaneously electric voltage of 2.1 V was applied using Keithley 2400. The tensile test was carried out according to ASTM standard D3039. Change in resistance was calculated based on $\Delta R/R_0$ where ΔR is the difference between the instantaneous resistance, R_i, and initial resistance, R_0. Gauge factor (GF) (sensitivity) was calculated in the linear region using equation 1 [8]

$$GF = \frac{\Delta R/R0}{\varepsilon} \tag{1}$$

where ε is strain.

5 RESULTS AND DISCUSSION

CNT/CNC composition at a ratio of (6.0:6.0 wt.%/wt.%) was printed on the surface of the composite using the screen printing method. The as-transferred patterns were used for subsequent tests. Figure 1 shows a microscope image of grid and line configurations strain sensors printed on the surface of the GFRP composite. Discontinuities are present, which can be attributed to the rough surface of the composite coupon. In this work, the effect of discontinuities on the electromechanical behavior was not investigated; however, improving the resolution of printing is the primary concern of the current research. The sensing legs' width and length were 989 ± 32 µm, and 675 µm, respectively.

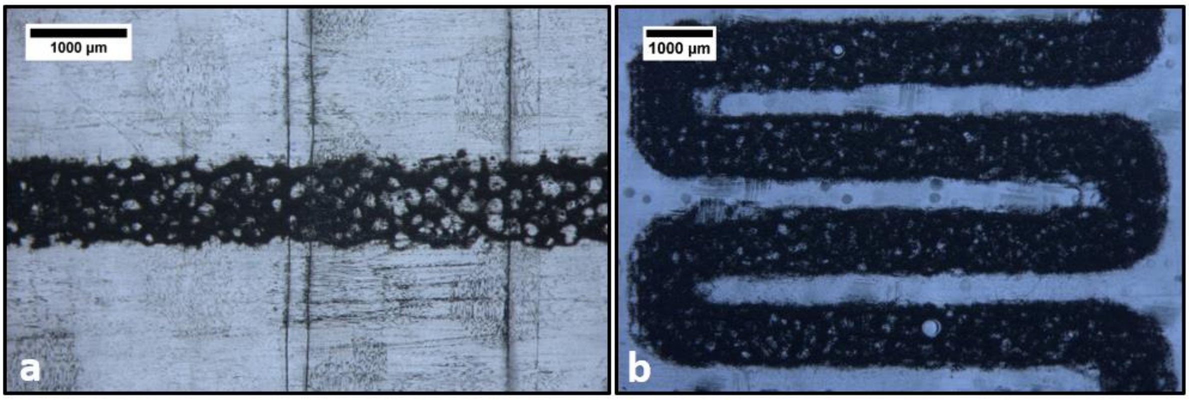


Figure 1: Light microscope image of printed sensors on the surface of GFRP composite coupon with two configurations: a) grid and b) line.

Two distinct strain gauge patterns were transferred on the surface of GFRP composite coupons. The strain gauge sensors (single line and conventional grid) are shown in the insets of Figure 2. The single-line configuration has one leg with a length of 675 µm. The conventional grid has 11 legs, each with a length identical to the single line configuration's leg, 675 µm.

Figure 2 shows the initial electrical resistances of the two patterns. The increasing layer of printing decreased electrical resistance. Increasing the number of layers helped fill up the voids on the sensor's surface, thus, facilitating better electrical network conductivity. Liu et al. reported similar results [9]. The initial resistance of the single line sensor after four layers of printing, 4.6 ± 0.2 Kohm, was smaller than the initial resistance of the grid sensor even after five layers of printing, 40.7 ± 7.2 Kohm. The difference in electrical resistance was considered consequential because the grid sensor has a higher number of legs, which increases the overall length of the resistor, thus increasing the sensor's electrical resistance. It is worth reporting that the initial resistance of the first layer of the grid sensor was higher than 200 Mohm (200 Mohm is the sourcesmeter's limit), which was not detected by the sourcemeter.

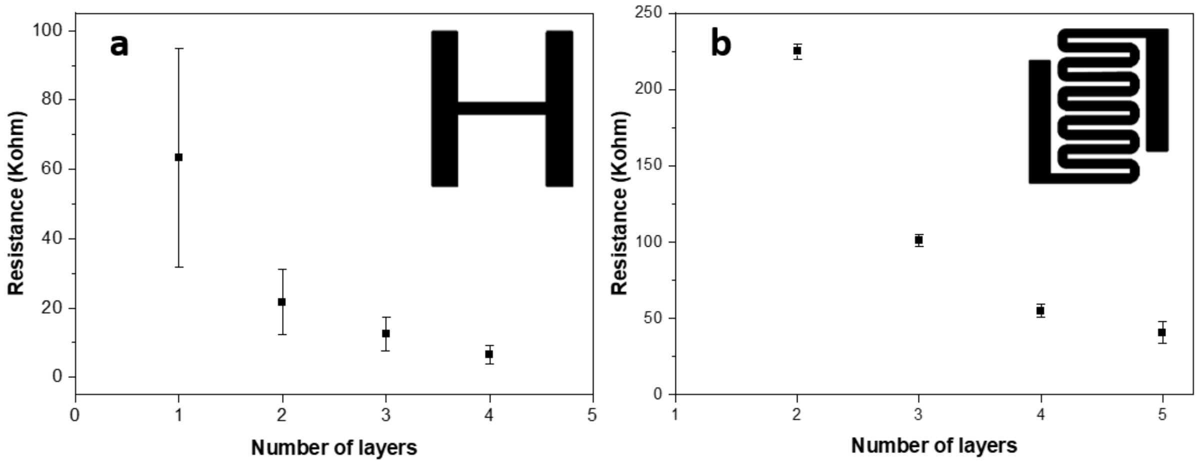


Figure 2: Electrical resistance as a function of a number of printed layers for a) single line configuration and b) grid configuration.

Figure 3 shows the piezoresistive behavior of single line and grid configuration sensors in tensile mode. As shown in Figure 3a, the single line sensor is nonlinear and not sensitive enough to measure mechanical changes occurring on the composite at small strains in the elastic region (the elastic region was estimated to end on 0.6% strain).

On the other hand, the grid configuration (conventional design) sensor was sensitive enough to measure elastic strains. The gauge factor (GF) in the elastic region was calculated to be 1. Han et al. showed that increasing the grid number (number of legs) increased GF in an elastic region, similar to what was observed here [10]. The reason was attributed to the higher total length grid sensor has in which the length of the grid sensor is eleven times longer than single line configuration.

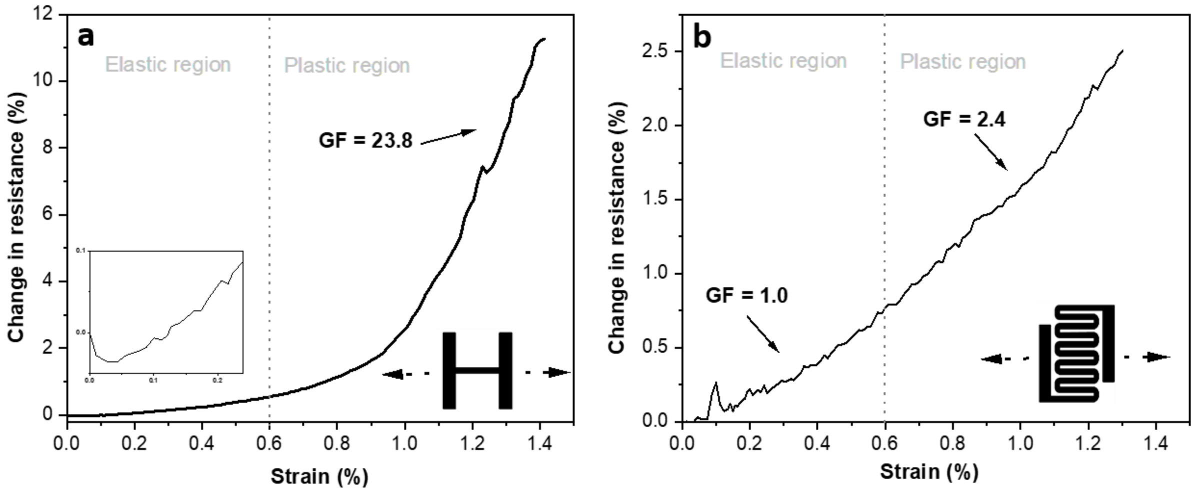


Figure 3: Piezoresistive behavior in the tensile mode of a) single line and b) conventional grid strain sensors.

In the plastic region, however, the single-line configuration sensor was much more sensitive, 23.8, than the grid configuration sensor, 2.4. The particular reason for such a difference may be due to the difference in sensitivity of the two sensors arising through the higher accumulation rate of damages occurring on the single line configuration since the grid configuration can sustain more damages on its network due to its longer geometry.

6 CONCLUSION AND FUTURE WORK

Transfer of strain gauge sensor using conductive inks on the surface of GFRP composite was demonstrated. This was facilitated by the screen printing method, which has the potential to be adopted on an industrial scale. The method reduces complexity by avoiding bonding between the strain gauge and the surface of the composite. The geometry of the strain sensors was shown to influence the piezoresistive behavior under tensile mode. For example, the single line configuration sensor was nonlinear in the elastic region compared with the grid design. In the plastic region, the single line configuration was much more sensitive (GF of 23.8 compared with 2.4 for the grid sensor). The methodology of the proposed strain gauge sensor attempts to eliminate the complex integration of external sensors, ensure compatibility with composite structures and facilitate a novel manufacturing method. The sensors showed promising performance.

On the other hand, challenges to improve sensitivity (beyond 2) in the elastic region and printing resolution are yet to be overcome. Thus, our current and future work focus on improving the performance and quality of the transferred sensors. Furthermore, more research is needed to quantify the effect of the area of electrodes of printed piezoresistive strain sensors on sensing capabilities.

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